Impact of Typhoons on the Western Pacific Ocean DRI: Numerical Modeling of Ocean Mixed Layer Turbulence and Entrainment at High Winds

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LONG-TERM GOALS

This study contributes to our long-term efforts toward understanding:

- Mixed layer dynamics
- Processes that communicate atmospheric forcing to the ocean interior

OBJECTIVES

This collaborative effort aims to measure and model the response of the upper ocean to strong typhoons both in simple, open ocean conditions and in the more complex conditions caused by ocean eddies, the Kuroshio and complex, shallow bathymetry. The measurements and modeling includes the impact of surface waves, air-sea fluxes and the temperature, salinity and velocity structure of the upper ocean. The goals of this effort are to understand key upper ocean processes, test upper ocean models, test key parameterizations of upper ocean physics used and study the feedback from the ocean to typhoon intensity.

APPROACH

The approach of the modeling component is to use field observations to force Large Eddy Simulation (LES) and upper ocean turbulence models in equivalent numerical cases and to use model-data comparison to test the theoretical basis of mixed layer turbulence scalings and parameterizations. The strategy is to test our physical theories and parameterizations of mixed layer dynamics against data by incorporating them realistically in turbulence-resolving LES models with embedded virtual measurements. Verification of the underlying theories can then be achieved through direct model-data comparison, using observations of ocean waves and turbulence under a wide range of oceanic conditions, and leading to improved parameterizations of upper ocean turbulence. The strong and isolated wind forcing in tropical cyclones provides an ideal environment for testing theories and parameterizations of the role of surface waves in the ocean mixed layer. This follows similar work in

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CBLAST exploiting the comprehensive view of boundary layer turbulence made possible by the combination of Lagrangian float and EM-APEX measurements.

WORK COMPLETED

A series of Typhoon LES model cases has been carried out to simulate the upper ocean response to spectrally distributed surface waves with wind-wave coherence varying with frequency. These are based on the spectra modeled and measured during CBLAST hurricanes. These simulations are being used to parameterize the effect of surface wave spectra on mixed layer energy and entrainment during hurricanes.

In this year, wave-modified versions of upper ocean mixing parameterizations have been developed, based on these LES simulations and upon comparisons between LES results and E. A. D'Asaro's database of Lagrangian float observations at moderate to high winds. Wave-modified versions have been developed for the K-Profile Parameterization (KPP) mixed layer model, and for the Mellor-Yamada 2.5 (MY2.5) closure scheme. The latter development (MY2.5) is based partly on the work of Kantha and Clayson (2004; KC04), but efforts to reproduce their results were not successful without applying significantly different constraints on stratified turbulence length scales. Despite assurances, multiple efforts to obtain KC04 model code for comparisons and further analysis of this issue have not been successful.

In addition to work on including wave effects in upper ocean mixing parameterizations, significant progress has been made in accounting for the impact excess float buoyancy on Lagrangian float measurements. A prescription for removing systematic errors due to float buoyancy from turbulence statistics of vertical velocity has been developed for a wide set of wind and wave-driven mixed layer cases (Harcourt & D'Asaro, submitted). T his study also reflects ONR-sponsored work under the Lateral Mixing and AESOP DRI's and these results are described in the Lateral Mixing report. Their significance in the context of high winds and wind-turbulence interactions bears in particular on the hypothesis of Stokes-Breaker interaction advanced by the simulations of Sullivan et al (2007) as it applies to highly nonlinear, strongly breaking surface waves in typhoons and hurricanes.

RESULTS

The LES models forced by wind stress and model surface waves via the Craik-Leibovich vortex force can predict mixed layer vertical kinetic energy and entrainment rates, provided that the surface wave field and drag coefficient are properly specified. A simulated case at Lagrangian float G22 below the wind maximum of Hurricane Frances (2004) is shown in Fig. 1.

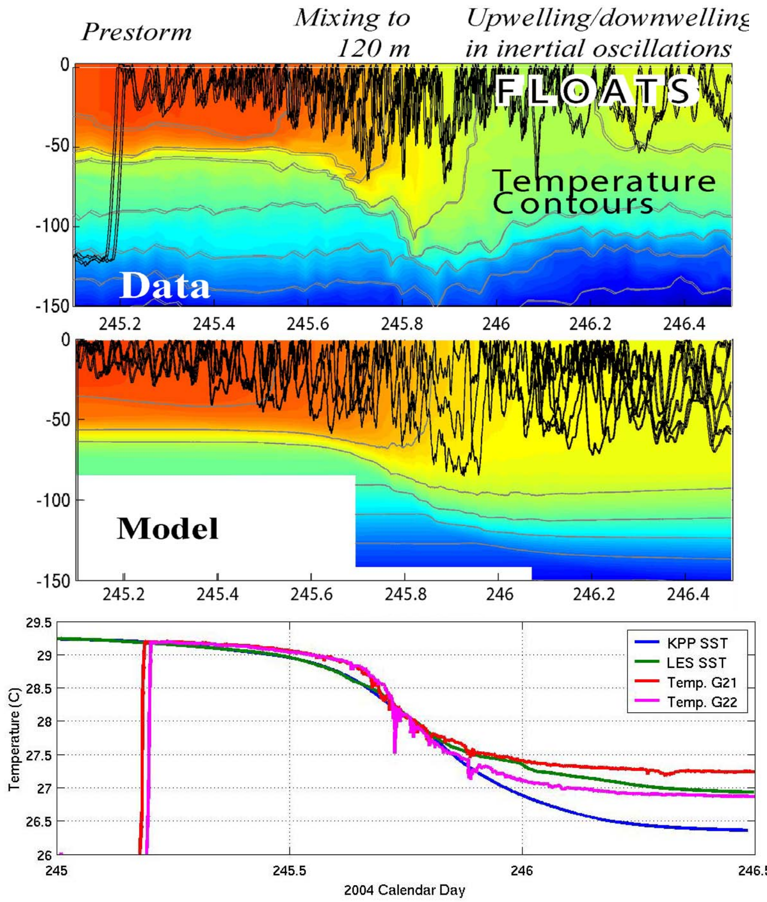

Figure 1: (top) shows Temperature (color and contours) from EM and Lagrangian floats G21 and G22 (Sanford, D'Asaro), overlaid with Hurricane Frances Lagrangian float observations. (middle) a corresponding LES model with floats (middle), vs. time and depth (m). Modeled float depth distributions and vertical TKE agree well with the data. Proper prediction of mixed layer depth changes will require further specification of upwelling due to larger scale dynamics, but LES sea surface temperature (bottom) compares well with Lagrangian float G22. An LES-equivalent column model based on KPP matches LES evolution as the wind rises, but predicts significantly more entrainment and cooling as wind drops, and compares less favorably with observations.

The evolution of mixed layer depth agrees until larger scale upwelling (D'Asaro et al 2007) intervenes. Even beyond that, the evolution of surface temperature continues to agree relatively well. Other than its role in the surface stress, no additional contributions from wave breaking appear to be necessary for prediction of mixed layer VKE or entrainment deepening. Comparisons with a column model based on the K-Profile Parameterization (KPP) agree when the wind is rising, but not in the rear of the storms when seas are confused and KPP entrainment is driven more by inertial shear in the pycnocline.

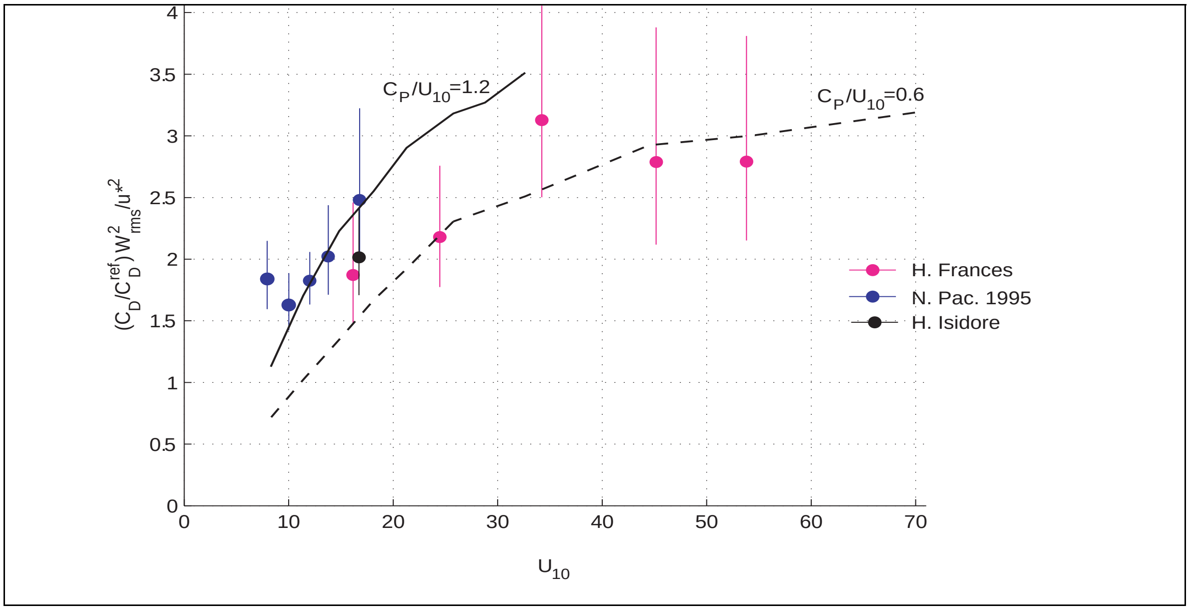

Figure 2: Float observations (color) and LES predictions (black) of bulk mixed layer vertical TKE scaled on wind kinetic energy U_{10}^2 (using C_D^{ref}=1e-3). Under moderate winds (blue symbols) simulations assuming mature (C_p/U_{10} =1.2, solid) seas fit well. Under extreme winds (CBLAST – purple & black), simulations assuming young (C_p/U_{10} =0.6, dashed) seas and a saturating drag coefficient fit well. Turbulence in the ocean mixed layer cannot therefore be specified from wind speed alone; wave properties and a proper drag coefficient are also needed. Data with a wide range of variability in wind speed and wave age is needed to test parameterizations of these effects. Typhoons are an ideal environment for this. Proper modeling of typhoon boundary layers requires an understanding of these effects.

An LES-derived parameterization (Harcourt and D'Asaro, 2008) based on wind speed and wave age, assuming pure wind seas, can predict measured mixed layer vertical kinetic energy (D'Asaro, 2001) under a wide range of conditions. The magnitude of VKE figures prominently in several mixed layer models, including KPP. The VKE is scaled by wind stress is a function of a modified turbulent Langmuir number $La_{SL} = (u^*/(u^S_{SL} - u^S_{ref}))^{1/2}$, based on the friction velocity u^* and the near-surface average u^S_{SL} of the Stokes drift u^S. A reference level u^S_{ref} from within the lower mixed layer is subtracted because vortex force production must vanish for a mixed layer with uniform Stokes drift. A distinction of this parameterization is that it applies equally to Langmuir turbulence in realistic wind seas with distributed spectra as well as to more the more widely considered idealized cases with monochromatic surface waves. Fig. 2 shows comparisons for both the very young seas found at high winds in Typhoons and Hurricanes, and for fully developed mature seas found at more moderate wind speeds in mid-latitude winter storms, demonstrating the range of conditions predicted within the framework of Craik-Leibovich theory by this parameterization.

Current upper ocean boundary layer models typically parameterize the effect of wind and waves using the friction velocity u_*. Surface wave effects are included in the KPP model by rescaling the model vertical velocity scale to conform under varying sea states to the scaling of VKE with La_{SL} and u^{*2} arrived at in Harcourt & D'Asaro (2008). Figure 3 illustrates the impact of this modification on KPP

predictions for a model storm based on the H-winds product and wave model simulations from Hurricane Frances. The main surface impact of including wave effects is that reduced entrainment due to the relative youth of waves at high winds leaves the resulting mixed layer shallower by up to 20 m in the right rear quadrant, and warmer by up to 0.4C. The relative effects on the wake are more substantial in changes to the gravitational potential energy of the water column in the modified KPP, which is as much as 50% larger than when sea state is not accounted for.

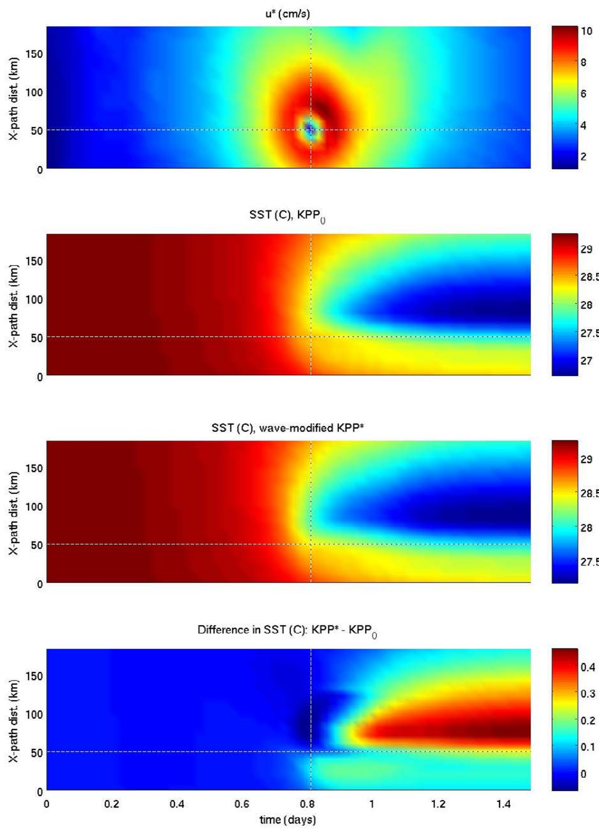

Figure 3: Top panel shows the evolution of model storm friction velocity at points spanning the model hurricane path. Middle panels show the evolution of SST under standard KPP (upper) and wave-modified KPP* (lower) resulting from turbulent entrainment. Bottom panel shows the difference in SST due to the inclusion of surface wave effects in KPP*.

To include wave effects in an MY2.5 type second moment closure model, turbulence production was included in both the TKE and length-scale dynamic equations after KC04. In this case, it was possible to constrain the model VKE directly and examine the impacts on upper-ocean mixing. However, the prescriptions of KC04 were found to not constrain the turbulence length scale well in the lower stratified portion of the deepening mixed layer under strong forcing. The length scale was instead constrained more directly by constraining it to the Ozmidov scale via the same mechanism as used for the near-surface wall-bounded scaling. By modifying the realizability conditions of the closure (i.e., preventing $w^2<q^2= u^2 +v^2 +w^2$), and allowing the surface length scale to be 5 times the Stokes e-folding depth scale, up to the mixed layer depth, a modified version of MY2.5 was developed that

comformed better to both observed turbulence characteristics and rates of entrainment, as illustrated below in Fig. 4.

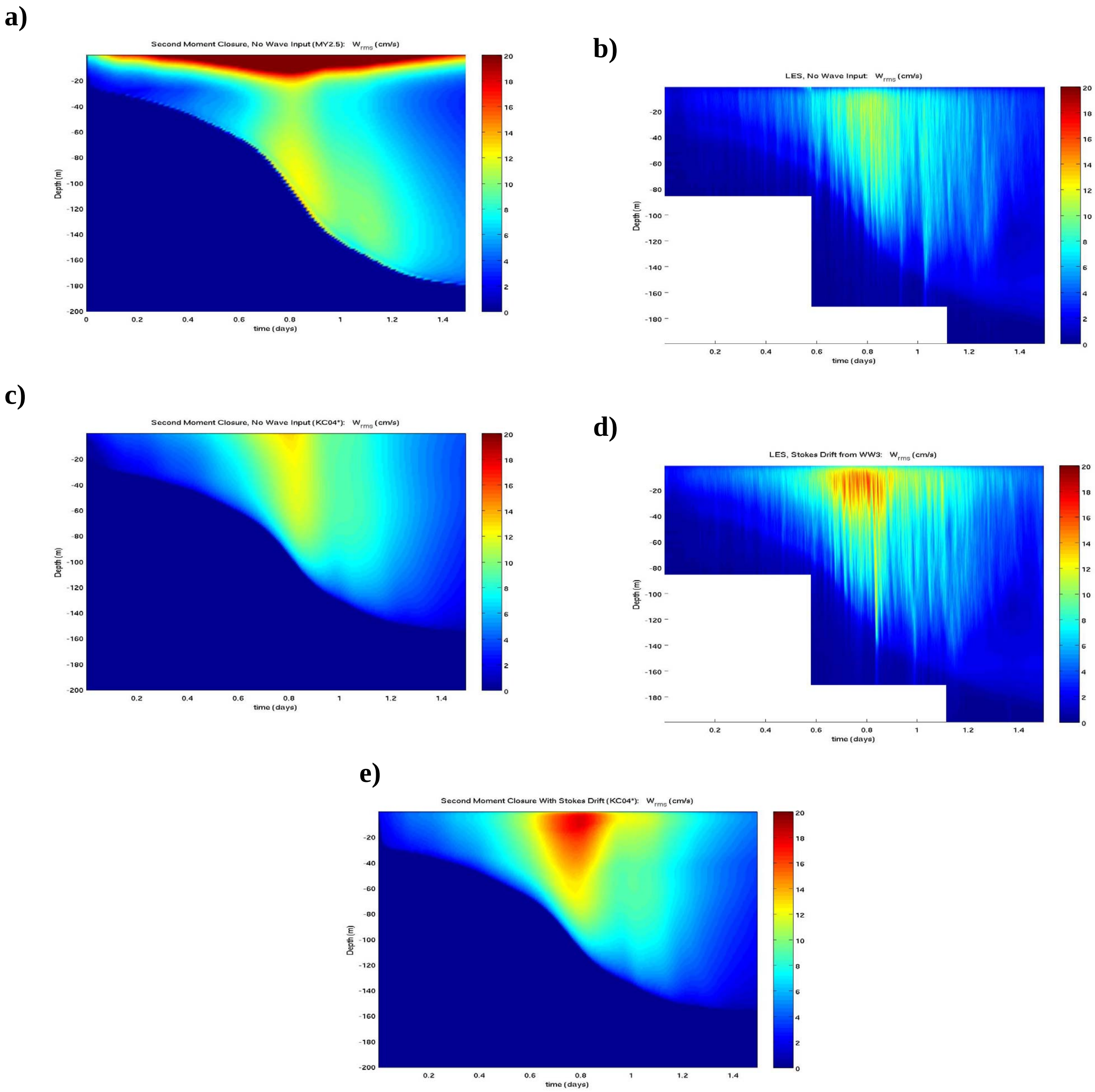

Figure 4: Vertical Kinetic Energy w^2 in LES and second moment closure models in response to wind and waves along the path of maximum winds, in: a) A standard MY2.5 closure with wave-breaking TKE production (i.e. NCOM); b) LES model without wave breaking or CL vortex force; c) modified KC04 closure without wave breaking or CL vortex force; d) LES model without wave breaking and with CL vortex force; e) modified KC04 closure without wave breaking and with CL vortex force

The reference MY2.5 case in Fig. 4a, based on NCOM model code, includes a TKE source term for wave breaking, after Craig & Banner (2004), but no Craik-Leibovich vortex production. Near-surface VKE levels entailed by this model are much higher than found in the LES model with vortex forcing (Fig. 5d) or in corresponding Lagrangian Float measurements. Furthermore, entrainment zone VKE is significantly elevated over mid-layer levels during rapid entrainment, suggesting the turbulence there is generated locally by shear production, and similar behavior is found in the KC04 wave-modified version of MY2.5. Neither LES results nor float observations support the presence of such a large intensification of VKE in the entrainment zone, and indicate turbulence levels are instead controlled by near-surface production. Constraining the turbulence length scale to the Ozmidov scale in the wave-modified version of KC04 improves this aspect of the predictions. Turning off the TKE production from wave breaking produces a VKE prediction from this second order model (Fig 4c,e) that is very consistent with the LES-modeled effect of omitting (Fig. 4b) or including (Fig 4e) Craik-Leibovich vortex force production.

IMPACT/APPLICATIONS

Surface waves are believed to play a key role in the upper ocean boundary layer, yet do not appear explicitly in any of the major boundary layer parameterizations used in ocean circulation or climate models. Addressing this defect will lead to mixed layer models with turbulence intensity and entrainment efficiency, scaled by wind stress, that increase with surface wave age, in the presence of swell. While subsurface shear may dominate pycnocline mixing under inertially resonant wind forcing conditions, variability in mixed layer energy due to surface waves will play a significant role in deepening the layer when this is not the case. A boundary layer model that includes sea state dependencies, in addition to the usual dependencies on surface stress, buoyancy flux, and subsurface shear, will ultimately be more accurate than one that does not.

RELATED PROJECTS

Typhoons DRI continues previous work in the Hurricane component of the CBLAST DRI.

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